MEMORANDUM REPORT ARBRL-MR-03041

HYPOTHETICAL ZERO YAW DRAG COEFFICIENT OF KINETIC ENERGY PROJECTILES BETWEEN M = 5 and M = 10

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August 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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ABERDEEN PROVING GROUND, MARYLAND

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From a review of existing techniques and extrapolation of lower velocity data, the drag characteristics of a typical kinetic energy projectile are proposed for application in the range 5<M<10.

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I. INTRODUCTION

In the particular kinetic energy branch of the field of tank warfare, various improvements in the kinetic energy projectile; e.g. higher length/ diameter ratios, monolithic construction and classified materials, compete with corresponding vehicle defensive improvements such as tipping screens, spaced heavy armor and equally classified materials.

It is obvious that the gun-launched kinetic energy projectile can be most efficiently employed in velocity regimes higher than those currently encountered in practice; but neither empirical data nor rigorous analytical technique is immediately available to exploit such potential. This report examines the free flight drag in the velocity region between Mach 5 and Mach 10 in conventional representation as composed from wave, viscous and base contributions analogous to the treatment of Reference 1. The procedure is essentially algebraic and the results are listed in tabulation. Transcription to desk calculator form is presented as an appendix.

II. PROCEDURE

Figure 1 is a schematic of a long rod, fin stabilized projectile and Figure 2 defines the nomenclature employed in the analysis. Standard sea level air properties are assumed.

A. For the body drag:

1. The wave drag coefficient (C_{DWB}) is given as

$$C_{DWB} = .7\ M^{-.28} \ell_n^{-1.73}$$

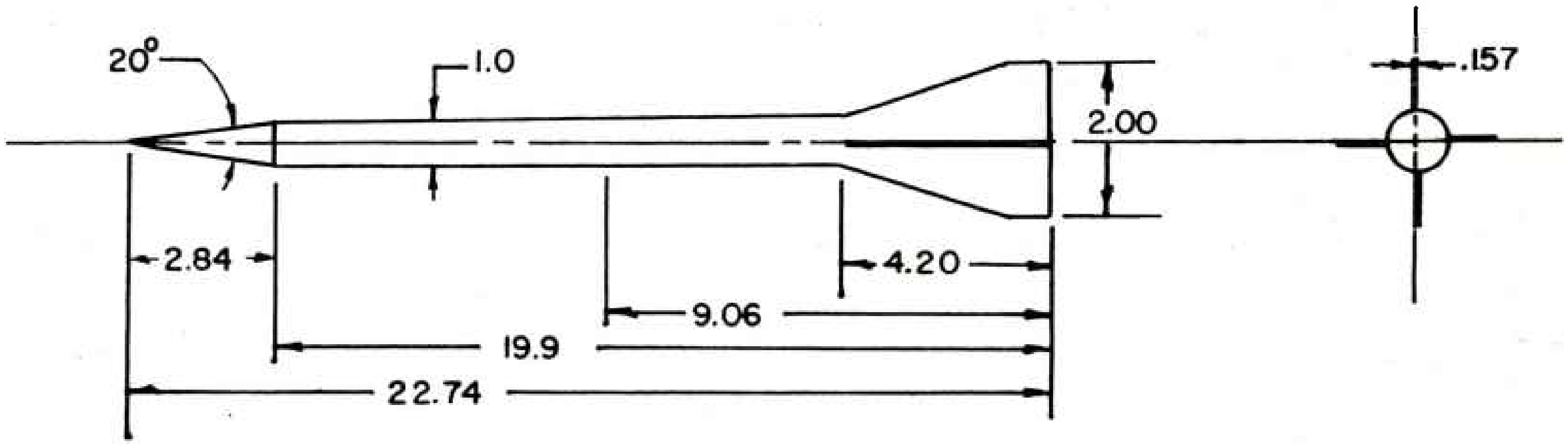
directly from Figure 8-29 of Reference 2 which is reproduced here as Figure 3. The quantity M is the Mach Number, and ℓ_n is the length of the projectile nose (in calibers). Both conical and ogival noses are described by this equation with restrictions imposed only in the case of a short nose length where $\frac{M}{\ell_n}$ <1.0 and 2<M<10. A data base exists to M = 5.

2. The hypersonic base drag (C_{DBB}) is specified from pragmatic considerations. It is assumed that the extreme decrement from the lower velocity flow is bounded by the value at M = 5 and zero. A patch

---

[1] *W. F. Donovan and B. B. Grollman, "Procedure for Estimating Zero Yaw Drag Coefficient for Long Rod Projectiles at Mach Numbers from 2 to 5", ARBRL-MR-02819, March 1978.* (AD#A054326)

[2] *"Design of Aerodynamically Stabilized Free Rockets" AMC Pamphlet 706-280, 1968.*



DIMENSIONS IN CALIBERS

Figure 1. Typical Kinetic Energy Projectile

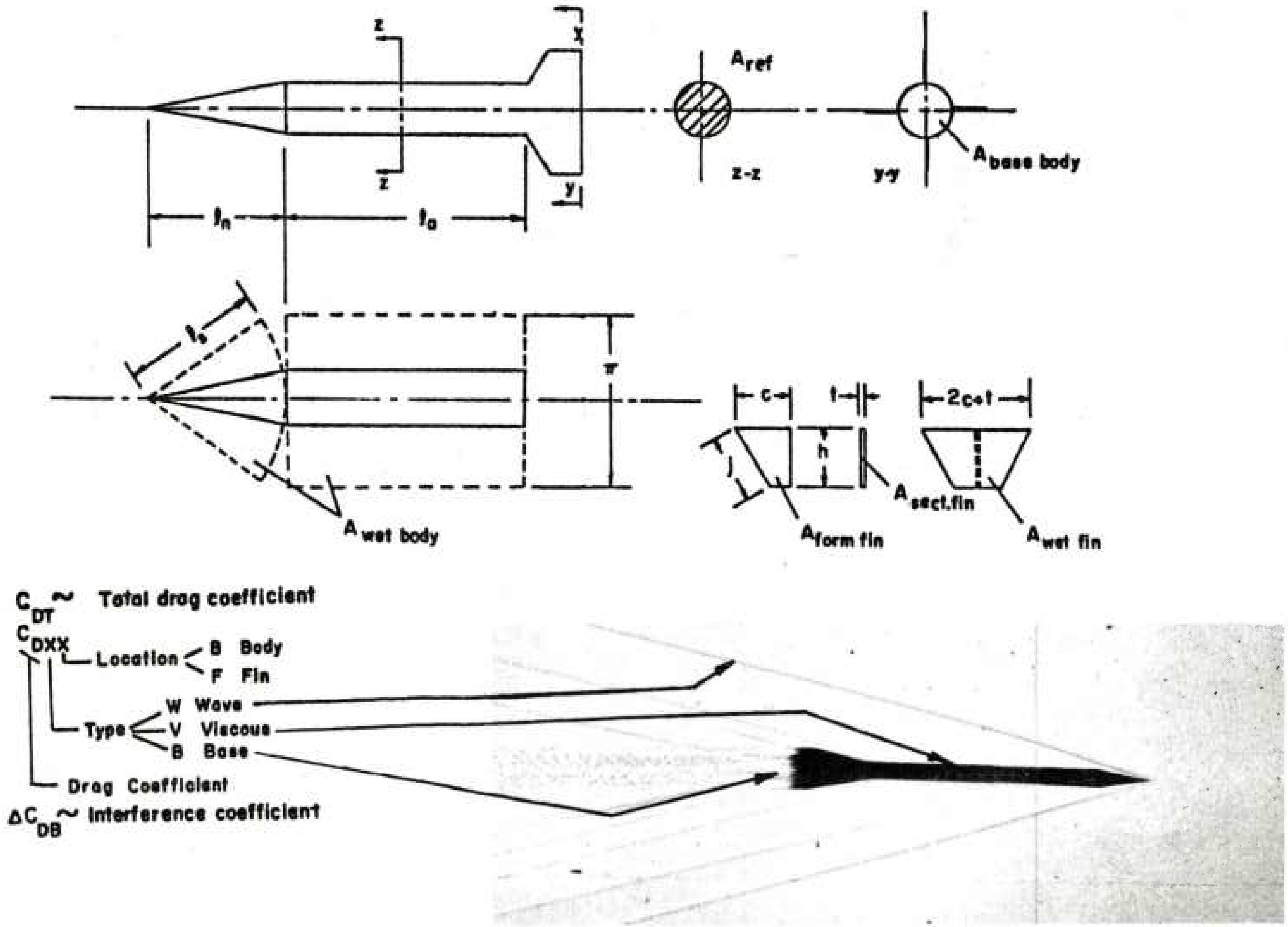


Figure 2. General Nomenclature Specification for Typical Projectile

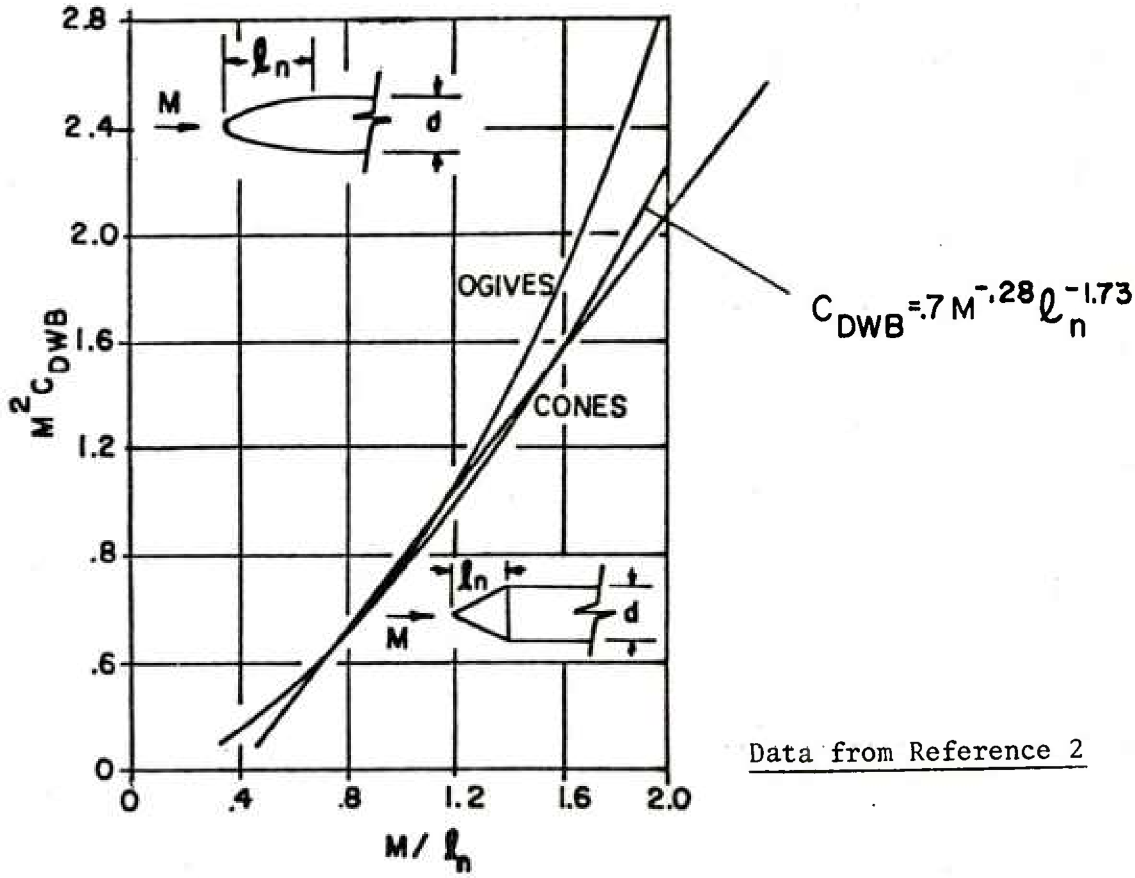


Figure 3. Nose Wave Drag Coefficient Correlation

procedure, which is described in Appendix A, is imposed and the result is a bilinear characteristic from M = 2 to M = 10 with the knee at M = 5. Available references offer little insight into the aerodynamics of hypersonic flow in the wake of cylindrical bodies. The wake flow behind cones has been investigated, however, and a survey of the results of these open literature studies is included in Appendix B. Thus

$$C_{DBB} = .040 - .003\ M \quad ,$$

proposed for use in the range 5<M<10.

3. The viscous drag component (C_{DVB}) is obtained by Mach extrapolation of Figures 8-39 and 8-40 of Reference 2, which is presented in Figure 4. Here, $C_{F'}$ is the flat plate friction factor, which is a function of M, $C_{F''}$ is an empirical constant equal to 1.51, as employed in Reference 1, and $C_{F'''}$ transposes the classical flat plate coefficients to cylindrical applications[3] and is taken as a constant equal to 1.15.

Whereby:

$$C_{DVB} = C_{F'}\ C_{F''}\ C_{F'''} \left(\frac{A_{\text{wetted surface}}}{A_{ref}}\right)$$

$$= 10^{-4}\ (13.84 - 1.184\ M)\ (1.51)\ (1.15) \left(\frac{A_{\text{wetted surface}}}{A_{ref}}\right)$$

$$= .000173\ (13.84 - 1.184\ M) \left(\frac{A_{\text{wetted surface}}}{A_{ref}}\right),$$

proposed for the range 5<M<10.

Any superposed drag due to aerodynamic disturbances from the driving grooves is assumed as part of the empirical constant $C_{F''}$. As in 2, the bilinear characteristic is retained. The viscous flow mechanics in hypersonic flow have been examined from divergent assumptions (refer to Appendix B) and are considered here from the conservative premise.

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[3] *L. M. Freeman and R. H. Korkegi, "Projectile Aft-Body Drag Reduction by Combined Boat-Tailing and Base Blowing", AFAPI-TR-75-111, February 1976.*

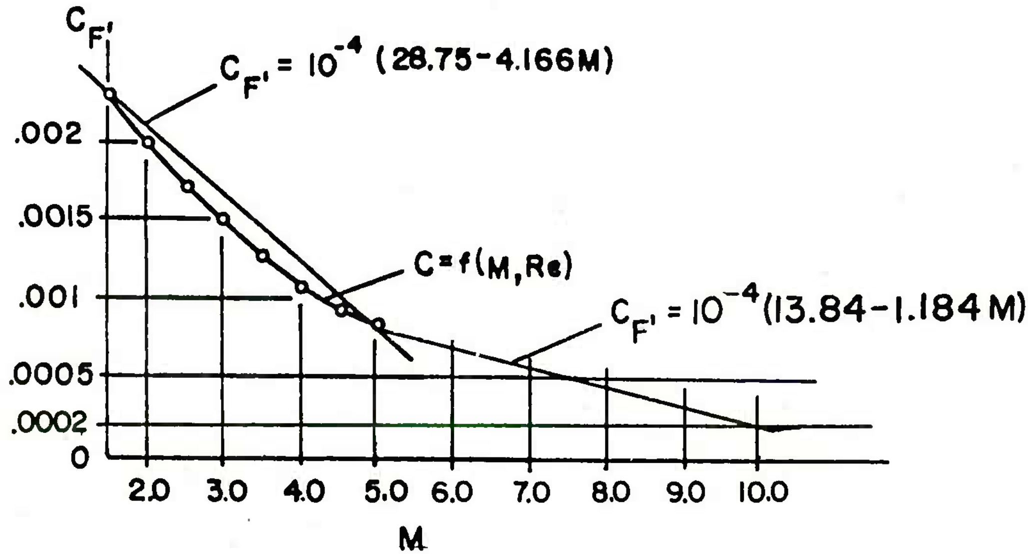

Figure 4. Conversion of Mach Number to $C_{F'}$

B. For the empennage:

1. The wave drag coefficient for the fins (C_{DWF}) is suggested by Reference 4 and is recommended for fins with a single bevel leading edge, where

$$C_{DWF} = \frac{n}{\beta} \left(\frac{t}{j}\right)^2 \left(\frac{A_{\text{wetted fin}}}{A_{\text{ref}}}\right),$$

proposed for the range of $2<M<10$. Reference 5 presents a similar form for biconvex profiles.

2. The fin base drag (C_{DBF}) is determined by an area ratio with the body base, or

$$C_{DBF} = n \left(\frac{A_{\text{sect fin}}}{A_{\text{base body}}}\right) C_{DBB} ,$$

where n is the number of fin blades per fin assembly. This report considers that the full thickness fin area represents the active drag cross section, which is a conservative assumption. The effects of fin-body interference may be neglected on the basis of magnitude (refer to Appendix C). Since the fin base area is considered as the extension of the body base area, the same Mach limitations are assumed.

3. The fin viscous drag (C_{DVF}) is taken as the area ratio of the respective wetted surfaces of the fin and body as modified by the flat plate cylinder correlation coefficient, leading to

$$C_{DVF} = n \frac{1}{1.15} \left(\frac{A_{\text{wetted fin}}}{A_{\text{wetted body}}}\right) C_{DVB} .$$

In viscous behavior, the fin is also an extension of the body.

C. The total zero-yaw drag coefficient is then equal to the sum of the individual contributions.

III. RESULTS

Figure 5 presents the graphical form of the analysis of the projectile drag coefficient for the Mach number range from M = 5 to M = 10. The discrete contributions of the individual components are available from Tables 1 and 2 and from the Hewlitt Packard calculator printout of the calculator program list given in Appendix D.

[4] *S. F. Hoerner, "Fluid Dynamic Drag", Published by the author, 1958.*

[5] *H. Schlichting, Boundary Layer Theory, McGraw-Hill Book Company, Inc., New York, 1960.*

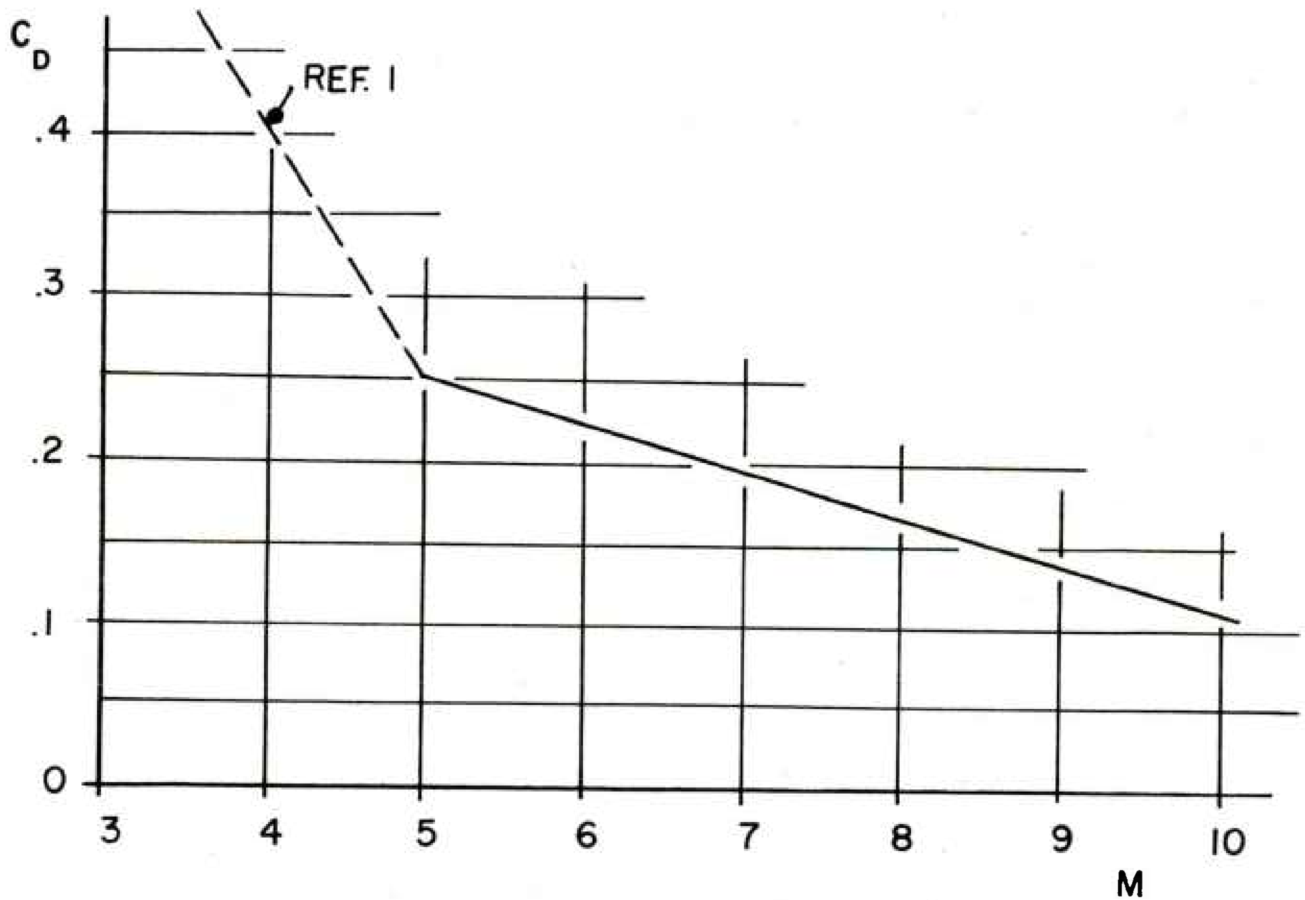

Figure 5. Drag Coefficient for Typical Kinetic Energy Projectile

TABLE 1. INPUT PARAMETERS FOR CALCULATING PROCEDURE

	BODY GEOMETRY										FIN GEOMETRY							
COLUMN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SYMBOL	l_n	l_{ab}	α	l_s	A_{ref}	A_{wet}		d			c	t	j	h	n	A_{form}	A_{wet}	A_{sect}
UNITS	cal	cal	rad	cal	cal^2	cal^2		cal			cal	cal	cal	cal		cal^2	cal^2	cal^2
	nose length	afterbody length	nose half angle	nose slant height, $l_n \sec \alpha$	reference area, $\pi/4$	wetted surface area, $\pi(.5l_s + l_{ab})$		diameter of of body			length of fin chord at root	trailing edge fin thickness	length of fin leading edge	length of fin half span	number of blades per fin assembly	planform area of fin blade	wetted surface area of fin blade	sectional area of fin blade
PROJECTILE	2.84	15.7	.176	2.88	.785	53.9		1.0			4.2	.157	3.38	1.0	4	2.6	5.2	.157

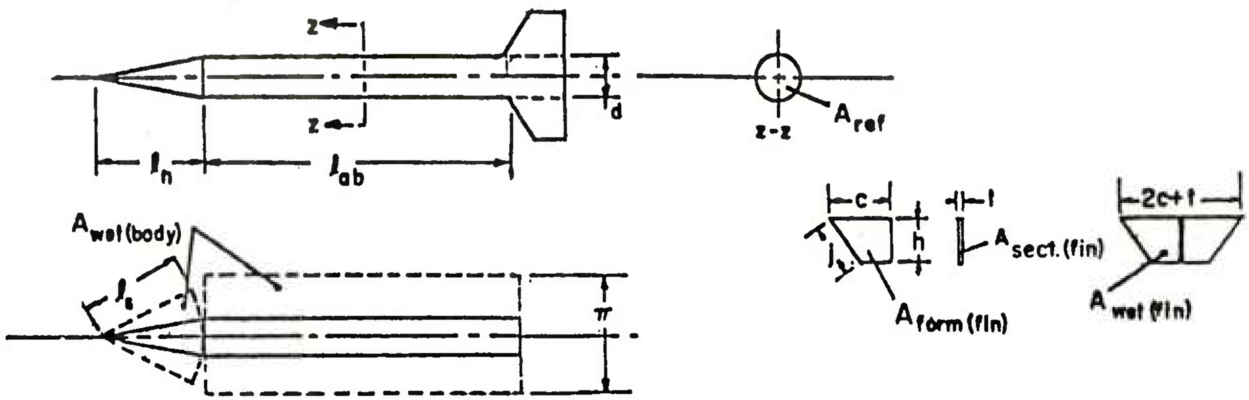

TABLE 2. OPERATING SCHEDULE FOR KINETIC ENERGY PROJETILE

COLUMN	21	22	23	24	25	26	27	28	29	30	31
SYMBOL	M	β	C_{DWB}	C_{DBB}	C_{DVB}	C_{DTB}	C_{DWF}	C_{DBF}	C_{DVF}	C_{DTF}	C_{DT}
DESCRIPTION	Mach		Wave - Body	Base-Body	Viscous - Body	Total-Body	Wave - Fin	Base - Fin	Viscous - Fin	Total - Fin	Total-Projectile
TEST NOTATION		$(M^2-1)^{1/2}$	$.7M^{-.28}\ell_n^{-1.73}$	$-.003M+.040$	$.000173(13.84-1.184M)(A_{wet}/A_{ref})$		$(n/\beta)(t/l)^2(A_{form}/A_{ref})$	$n(A_{sect}/A_{ref})C_{DBB}$	$n(A_{wet-fin}/A_{wet-body})(C_{DVB}/1.15)$		
CALCULATION			$.7(21)^{-.28}(1)^{-1.73}$	$-.003(21)+.040$	$.000173(13.84-1.184(21))(6/5)$	$23+24+25$	$(15/22)(12/13)^2(16/5)$	$15(18/5)24$	$15(17/6)25(.897)$	$27+28+29$	$26+30$
	5.0	4.899	.074	.025	.094	.193	.006	.020	.032	.058	.251
	6.0	5.916	.070	.022	.080	.172	.005	.018	.027	.050	.222
	7.0	6.928	.067	.019	.066	.152	.004	.015	.022	.041	.199
	8.0	7.937	.064	.016	.052	.132	.004	.013	.017	.034	.165
	9.0	8.944	.062	.013	.038	.113	.003	.010	.013	.026	.139
	10.0	9.950	.060	.010	.024	.094	.003	.008	.008	.019	.113

TABLE 2. OPERATING SCHEDULE FOR KINETIC ENERGY PROJECTILE (continued)

Printed Output

Mach number	M	10.00000000	***
Body wave	C_{DWB}	0.060375023	***
Body base	C_{DBB}	0.010000000	***
Body visoous	C_{DVB}	0.023724305	***
Body total	C_{DTB}	0.094099329	***
Fin wave	C_{DWF}	0.002855548	***
Fin sectional	C_{DBF}	0.007995944	***
Fin viscous	C_{DVF}	0.007924091	***
Fin total	C_{DTF}	0.018775584	***
Projectile	C_D	0.112874912	***

10.00000000	***
0.060375023	***
0.010000000	***
0.023724305	***
0.094099329	***
0.002855548	***
0.007995944	***
0.007924091	***
0.018775584	***
0.112874912	***

9.000000000	***
0.062182676	***
0.013000000	***
0.037769094	***
0.112951770	***
0.003176597	***
0.010394728	***
0.012615153	***
0.026186477	***
0.139138246	***

8.000000000	***
0.064267605	***
0.016000000	***
0.051813883	***
0.132081488	***
0.003579619	***
0.012793511	***
0.017306215	***
0.033679345	***
0.165760833	***

7.000000000	***
0.066715979	***
0.019000000	***
0.065858672	***
0.151574650	***
0.004100969	***
0.015192294	***
0.021997276	***
0.041290540	***
0.192865190	***

6.000000000	***
0.069658635	***
0.022000000	***
0.079903460	***
0.171562096	***
0.004802563	***
0.017591078	***
0.026688338	***
0.049081979	***
0.220644075	***

5.000000000	***
0.073307045	***
0.025000000	***
0.093948249	***
0.192255294	***
0.005799646	***
0.019989861	***
0.031379400	***
0.057168907	***
0.249424200	***

REFERENCES

1. W. F. Donovan and B. B. Grollman, "Procedure for Estimating Zero Yaw Drag Coefficient for Long Rod Projectiles at Mach Numbers from 2 to 5", ARBRL-MR-02819, March 1978. (AD#A054326)

2. "Design of Aerodynamically Stabilized Free Rockets", AMC Pamphlet 706-280, 1968.

3. L. M. Freeman and R. H. Korkegi, "Projectile Aft-Body Drag Reduction by Combined Boat-Tailing and Base Blowing", AFAPI-TR-75-111, February 1976.

4. S. F. Hoerner, "Fluid Dynamic Drag", Published by the author, 1958.

5. H. Schlichting, "Boundary Layer Theory", McGraw-Hill Book Company, Inc., New York, 1960.

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Kuethe, A.M., Schetzer, J.D., "Foundations of Aerodynamics", John Wiley and Sons, Inc., New York, 1967, p 381; Examination of continuum vs slip flow.

Liepman, H.W., Roshko, A., "Elements of Gasdynamics", John Wiley and Sons, Inc., New York, 1957, pp 122, 218 - 269, 343; Mach nose effects, Hypersonic similarity. Slender body theory. Skin friction to M = 10.

Murphy, C.H. "Free Flight Motion of Symmetric Missiles", Ballistic Research Laboratories Report No. 1216, July, 1963 (AD 442757), pp 9-17, 29, 131 - 135; Aerodynamic drag. Skin friction parameters as affected by heat transfer. (AD#442757)

Shapiro, A.H., "The Dynamics and Therodynamics of Compressible Fluid Flow, Vol. II". The Ronald Press Company, New York, 1953, pp 1109 - 1125; Discussion of Mach number, skin friction, etc., on cones and cylinders in hypersonic flow.

Stivers, L.S. Jr. "Calculated Pressure Distributions and Components of Total Drag Coefficients for 18 Constant Volume Slender Bodies of Revolution at Zero Incidence for Mach numbers from 2.0 to 12.0 with Experimental Aerodynamic Characteristics for Three of the Bodies", NASA TN D-6536, October, 1971. Title describes context of report.

Kaufmann,W., "Fluid Mechanics", McGraw-Hill Book Company, Inc., New York, 1963, p. 397, Flat plate C_D to Mach 10.

Trujillo, A.A., "Summary of Static Stability and Drag Characteristics of Axisymmetric Low-Drag Shapes for the Subsonic to Hypersonic Mach Number Range", Sandia Laboratories Research Report SC-RR-68-304, August 1968, Drag predictions to M = 12.

LIST OF SYMBOLS

$A_{base\ body}$	Area of body exposed to base pressure $(cal)^2$
$A_{sect\ fin}$	Area of fin exposed to base pressure $(cal)^2$
A_{ref}	Reference area (.785 cal^2)
$A_{wetted\ surface}$	Area of particular surface assigned viscous flow drag (cal^2)
C_D	Total drag coefficient (Reference Symbol) $= \dfrac{2D}{\rho v^2 A_{ref}}$
C_{DBB}	Pressure drag coefficient - body
C_{DBF}	Pressure drag coefficient - fins
C_{DT}	Total drag coefficient
C_{DTB}	Total body drag coefficient
C_{DTF}	Total fin drag coefficient
C_{DVB}	Viscous drag coefficient - body
C_{DVF}	Viscous drag coefficient - fins
C_{DWB}	Wave drag coefficient - body (nose)
C_{DWF}	Wave drag coefficient - fin
Δ_{CDB}	Interference drag coefficient
$C_{F'}$	Skin friction factor for flat plate viscous flow
$C_{F''}$	Empirical constant
$C_{F'''}$	Conversion factor between flat plate and cylindrical viscous flow
D	Drag Force
M	Mach number
Re	Reynolds number

LIST OF SYMBOLS (continued)

b	Intercept of C_D - M characteristic
c	Chord length of base fin (cal)
d	Representative diameter of cylindrical reference area (1.0 cal)
h	Height of fin blade (cal)
j	Length of leading edge of fin (cal)
k	Slope of C_D - M characteristic
ℓ_a	Length of after body of projectile (cal)
ℓ_n	Axial length of projectile nose (cal)
ℓ_{sn}	Slant height of projectile nose (cal)
n	Number of blades per fin assembly
t	Representative fin thickness (cal)
w	Slope of $C_{F'}$ - M characteristic
v	Projectile velocity (cal/sec)
z	Intercept of $C_{F'}$ - M characteristic
β	Thermodynamic parameter $(M^2 - 1)^{1/2}$
ρ	Ambient air density

SPECIAL NOTATION

H-P 97 refers to the Hewlitt Packard calculator for which the program listing of Appendix D is written.

References to "hypersonic flow" indicate the Mach regime $5<M<10$. This designation is arbitrary.

APPENDIX A

PATCH PROCEDURE FOR TRANSITION TO HYPERSONIC REGIME

The body base drag coefficient for $2<M<5$ is given by

$$C_{DBB} = - .048\ M + .265$$

and acquires a value of .025 at M = 5. For the assumed decrement to .010 at M = 10:

$$- .048\ M + .265 = - k\ M + b\ ,$$

or

$$025 = b - 5\ k$$

with

$$.01 = (b - 10\ k)\ ,$$

whereby

$$b = .003$$

and

$$k = .04\ .$$

Thus

$$C_{DBB} = .04 - .003\ M\ .$$

The skin friction coefficient is similarly determined. At M = 10 the extrapolated decrement produces $C_{F'} = .0002$. This leads to

$$28.75 - 4.166\ M = z - w\ M\ ,$$

giving

$$z = 13.84\ ,$$

with

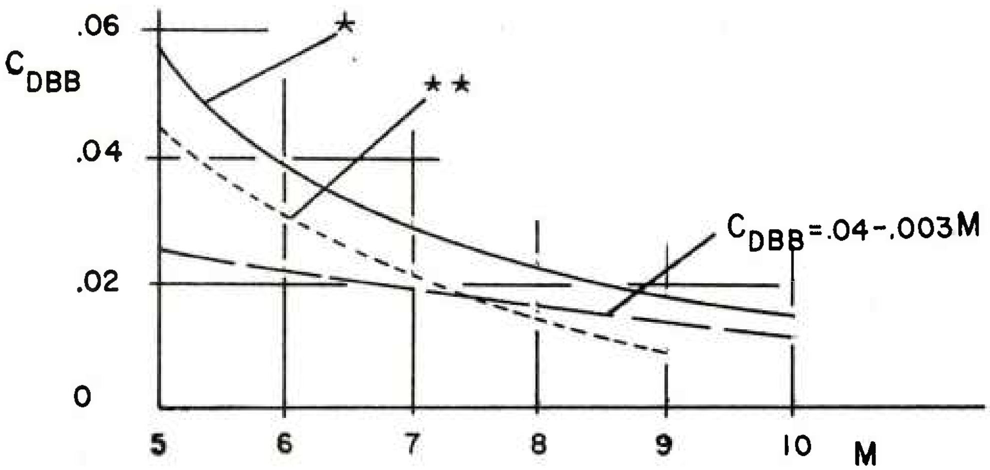
$$w = 1.184\ .$$

as suitable coefficients for the range $5<M<10$.

APPENDIX B

DISCUSSION OF BIBLIOGRAPHIC DATA

Lyons and Brown*, and Zarin**, offer results of work on cones. The Lyons and Brown base drag coefficient assumes a perfect vacuum in the immediate wake of the body while the Zarin data is predicated on pressure measurements in the model mounted in a wind tunnel facility. The results are compared with values calculated from the current report.



Although the pure cone C_{DBB} is higher than that predicted on the basis of the present report, this represents no contradiction since any non-vacuum base flow will give this result. The Zarin data agrees at M = 6.5 within 20% and at M = 8 within 7%.

The viscous contribution to the drag is treated by Lyons and Brown* as a boundary layer phenomena with additional components due to induced pressure and transverse curvature effects. Zarin** considers the viscosity to be negligible in comparison with the other terms. Stivers*** offers a conventional treatment whereby the laminar regime is superseded by a transitional and a turbulent flow, and then converts the body of revolution to equivalent flat plate configuration. This present report simply extrapolates from lower Mach number data and agrees, approximately since the Lyons and Brown data is lumped with the wave drag, with the Lyons and Brown results.

* *W. C. Lyons, Jr. and H.S. Brown, "The Drag of Slightly Blunted Slender Cones", NOLTR 68-3, January 1968.*

** *N. A. Zarin, "Base Pressure Measurements on Sharp and Blunt 9° Cones at Mach Numbers from 3.50 to 9.20", BRL MR 1709, November 1965.*(AD#369084)

****L.S. Stivers, Jr. "Calculated Pressure Distributions and Components of Total Drag Coefficients for 18 Constant Volume Slender Bodies of Revolution at Zero Incidence for Mach Numbers from 2.0 to 12.0 with experimental Aerodynmaic Characteristics for Three of the Bodies", NASA TN D-6536, October, 1971.*

APPENDIX C

FIN-BODY INTERFERENCE DRAG COEFFICIENT INCREMENT

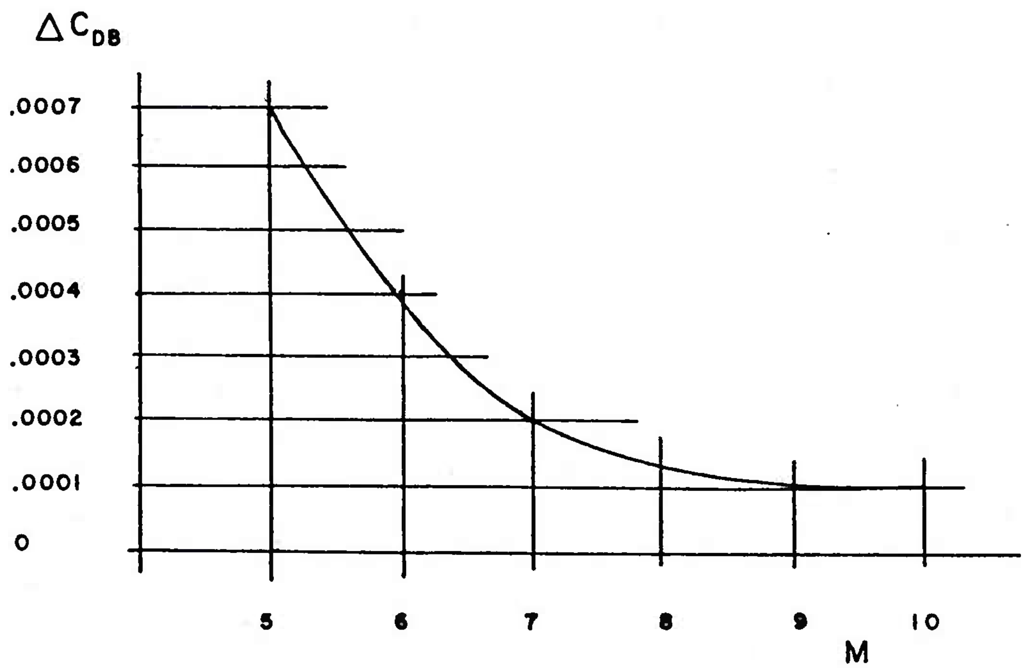
From Reference 4,

$$\Delta C_{DB} = \frac{t}{c} \left[\frac{.825}{M^2} - \frac{.05}{M}\right] \left[n\right] \left[\frac{A_{sect}}{A_{ref}}\right]$$

where

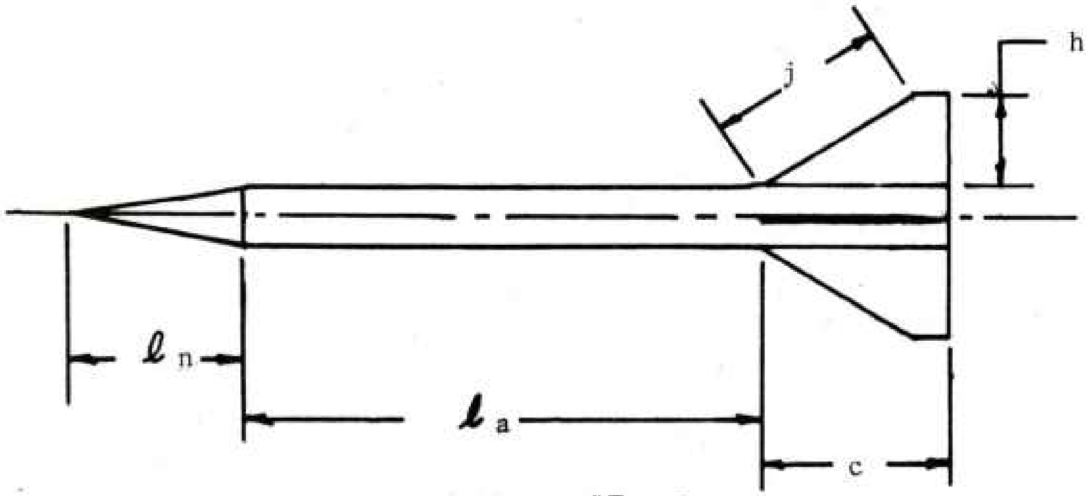
$t = .157$ cal,
$c = 4.2$ cal,
$n = 4$,
$A_{sect} = .157$ cal^2, and
$A_{ref} = .7854$ cal^2,

which leads to the result shown below.



APPENDIX D

PROGRAM LISTING FOR H-P 97 DESK CALCULATOR



Input Storage Registers

1	ℓ_n	Nose length
2	ℓ_a	Afterbody length
3	h	Fin blade height
4	t	Fin thickness
5	c	Fin blade length at root
6	j	Fin leading edge length
7	n	Number of fin blades
I	M	Mach number

Note that the program automatically decrements in unit Mach gradient. Decimal gradients can be employed by insertion at step 187.

Printed Output

Mach number	M	10.00000000 ***
Body wave	C_{DWB}	0.060375023 ***
Body base	C_{DBB}	0.010000000 ***
Body viscous	C_{DVB}	0.023724305 ***
Body total	C_{DTB}	0.094099329 ***
Fin wave	C_{DWF}	0.002855548 ***
Fin sectional	C_{DBF}	0.007995944 ***
Fin viscous	C_{DVF}	0.007924091 ***
Fin total	C_{DTF}	0.018775584 ***
Projectile	C_D	0.112874912 ***

Program Listing

```
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002   RCLI   36 46
003   PRTX     -14
004     LN      32
005      .     -62
006      2      02
007      8      08
008    CHS     -22
009      x     -35
010    e^x      33
011   STOA   35 11
012    CLX     -51
013   RCL1   36 01
014     LN      32
015      1      01
016      .     -62
017      7      07
018      3      03
019    CHS     -22
020      x     -35
021    e^x      33
022   RCLA   36 11
023      x     -35
024      .     -62
025      7      07
026      x     -35
027   PRTX     -14
028   STOA   35 11
029    CLX     -51
030   RCLI   36 46
031      .     -62
032      0      00
033      0      00
034      3      03
035    CHS     -22
036      x     -35
037      .     -62
038      0      00
039      4      04
040      0      00
041      +     -55
042   PRTX     -14
043   STOB   35 12
044    CLX     -51
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046	X²	53
047	.	-62
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049	X²	53
050	+	-55
051	√X	54
052	.	-62
053	5	05
054	x	-35
055	RCL2	36 02
056	+	-55
057	Pi	16-24
058	x	-35
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073	CLX	-51
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076	.	-62
077	1	01
078	8	08
079	4	04
080	CHS	-22
081	x	-35
082	1	01
083	3	03
084	.	-62
085	8	08
086	4	04
087	+	-55
088	RCLC	36 13
089	x	-35
090	PRTX	-14
091	STOC	35 13
092	RCLA	36 11
093	+	-55
094	RCLB	36 12
095	+	-55
096	PRTX	-14
097	STO8	35 08
098	CLX	-51
099	RCL3	36 03
100	RCL6	36 06
101	÷	-24
102	SIN⁻¹	16 41
103	TAN	43
104	STOE	35 15
105	RCL3	36 03
106	X²	53
107	RCLE	36 15
108	÷	-24
109	2	02
110	÷	-24
111	STOE	35 15
112	RCL3	36 03
113	÷	-24
114	2	02
115	x	-35
116	CHS	-22
117	RCL5	36 05
118	+	-55
119	RCL3	36 03
120	x	-35
121	RCLE	36 15
122	+	-55
123	STOA	35 11
124	Pi	16-24
125	÷	-24
126	4	04
127	x	-35
128	STOE	35 15
129	RCL4	36 04
130	RCL6	36 06
131	÷	-24
132	X²	53
133	RCLE	36 15
134	x	-35
135	RCL7	36 07
136	x	-35
137	STOE	35 15
138	CLX	-51
139	RCLI	36 46
140	X²	53
141	1	01

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142      -         -45
143     √X          54
144    RCLE      36 15
145      ÷         -24
146    1/X          52
147    PRTX        -14
148    STOD      35 14
149    RCLB      36 12
150    RCL7      36 07
151      x         -35
152    RCL3      36 03
153      x         -35
154    RCL4      36 04
155      x         -35
156     Pi       16-24
157      ÷         -24
158      4          04
159      x         -35
160    PRTX        -14
161    STOE      35 15
162     CLX        -51
163    RCLA      36 11
164      2          02
165      x         -35
166    RCL9      36 09
167      ÷         -24
168    RCLC      36 13
169      x         -35
170    RCL7      36 07
171      x         -35
172      1          01
173      .         -62
174      1          01
175      5          05
176      ÷         -24
177    PRTX        -14
178    RCLE      36 15
179      +         -55
180    RCLD      36 14
181      +         -55
182    PRTX        -14
183    RCL8      36 08
184      +         -55
185    PRTX        -14
186     SPC      16-11
187    DSZI   16 25 46
188    GTOC      22 13
189     RTN         24
190     SPC      16-11
191    GTOC      22 13
192     RTN         24
193    GSBC      23 13
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